Radiation Test Results for Interpoint Power Converters

Allan H. Johnston
Gary M. Swift

August 23, 2001

Office 514
Jet Propulsion Laboratory
Pasadena California

INTRODUCTION

The Interpoint SMHF28 series of power converters is designed to be radiation hardened to levels of 100 krad(Si), guaranteed by the manufacturer. There are several critical components within these converters, including an optocoupler, a special MOSFET driver chip, a medium-speed comparator, and power MOSFETs that provide current to the transformer. The manufacturer has hardened this design by (1) using special radiation-hardened power MOSFETs, (2) substituting a hardened optocoupler in place of the optocoupler that is used in the standard (unhardened) design, and (3) relying on existing radiation test data for individual components, such as the TSC4426 MOSFET driver to verify that the components will work satisfactorily to at least 100 krad(Si).

ESA recently performed radiation tests on samples of these converters, using cobalt-60 gamma rays at a dose rate of 2 rad(Si)/minute. These results were quite surprising, showing that the converters *failed* at radiation levels between 6.5 and 8 krad(Si). Lockheed-Martin subsequently verified those results, testing three converters under the same test conditions. They observed failures on converters at total dose levels between 4.4 and 5.4 krad(Si), slightly lower than the ESA results because of a different set of test conditions. Those results are summarized briefly in Table 1 below, including additional results for a converter that was irradiated in a non-operating mode with no bias applied. That device did not fail until 27.7 krad(Si), based on electrical tests that were done at periodic intervals during the irradiation sequence.

Table 1. Failure Levels of Several Converters at Intermediate Dose Rates

Part Number	Date Code	Organization	Dose Rate [rad(Si)/min]	Failure Criterion	Failure Level [krad(Si)]	Comments
SMHF2805S/ HR	9808	ESA	2	28 V	6.5	Converter within gyro unit
SMHF2805S/ HR	9925	ESA	2	total failure	8.0	Converter within gyro unit
SMHF2805S/ MR	9949	LMA	2	28 V	6.0	Tested without heat sink
SMHF2805DF /MR	9950	LMA	2	28 V	5.1	Heat sink used
SMHF2805DF /MR	9949	LMA	2	28 V	4.4	Heat sink used
SMHF2805SH /HR	112	LMA	2	28 V	5.4	Heat sink used
SMHF2805S/ KR	9926	LMA	2	28 V	27.7	Unbiased irradiation

Because of these results, a series of radiation tests were done by JPL to evaluate the radiation response of the converter as well as the internal component which was expected to be the cause of the failure, the TCS4426. Interpoint the TCS4426 because of special probe measurements done by Interpooint on one of the irradiated converters. The tests done by JPL include tests with cobalt-60 gamma rays at intermediate and high dose rates; tests with 62-MeV protons; and tests with 10-keV X-rays that selectively irradiated individual components within the converter. This report summarizes the results of those tests.

RADIATION AND TEST ENVIRONMENTS

A. Orbital Environment

The JASON spacecraft operates at an altitude of 1338 km, with 98 º inclination. It is essentially the same orbit experienced by Topex-Poseidon, but the requirements are slightly higher because the solar activity is different during the time period that JASON is required to operate. Nearly all of the ionizing radiation that is present in internal electronic boxes is in the form of high-energy protons (lower energy particles and electrons are shielded by enclosures). Calculations by Dr. Insoo Jun of JPL using a detailed mass model of the star tracker assembly on Jason have shown that the worst-case total dose expected for the Jason mission is 12.7 krad(Si); this does not include any extra factors such as a radiation design margin.

The proton spectrum for Jason has a higher mean energy compared to spacecraft that operate at lower altitudes, nominally 120 MeV. Test results using monoenergetic protons need to be corrected to account for the fact that there is a continuous spectrum of protons in the actual environment, with the realization that most of the protons have energies that are significantly above the proton energies where tests on the converters have been done.

B. Test Environments

<u>Protons</u>

Clearly the best way to test the converters is with high-energy protons, because that test environment most closely matches the actual environment within the spacecraft. However, proton tests are more costly and difficult to do, and consequently only a limited number of tests have been done with protons. The other concern is how to relate the ionizing radiation component from protons to damage in devices. That is partly dependent on what internal mechanism is involved.

For MOS devices, there is very little difference in the net trapped charge within gate oxides between high-energy protons and other test environments. However, that is not the case for thick oxides with low electric fields, such as the isolation or field oxide that is present in CMOS integrated circuits. High-energy protons produce less net charge in that type of structure, up to a factor of two less, depending on the proton energy and oxide properties. Thus, there are reasons to expect less damage for equivalent amounts of ionization from protons compared to other types of particles. However, the magnitude of that difference depends on proton energy as well as whether the radiation response is due to changes in the gate or field oxide.

<u>Cobalt-60 Gamma Rays</u>

The de-facto standard for ionizing radiation tests is cobalt-60 gamma rays, which have an energy of approximately 1.2 MeV. These particles are extremely penetrating. Ionization within semiconductor oxides is actually caused by Compton electrons that are produced when the gamma rays pass through the semiconductor or oxide region. Thus, the ionization is really due to a distribution of internally generated electrons, with mean energies of about 600 keV. Tests with cobalt-60 gamma rays may be somewhat conservative for environments that are dominated by protons because of differences in charge yield and recombination in thick oxide regions.

One complication for gamma ray tests is the presence of low energy scattered gamma rays from surrounding material. Test standards specify that devices should be surrounded by a thin sandwich of lead and aluminum (the lead is at the outer surface, and essentially absorbs low energy gamma rays). Tests done without this type of shield can be in error by as much as 25%.

Low Energy X-Rays

Low energy X-rays also produce ionizing radiation, and they are convenient laboratory sources with the advantage that it is easy to shield X-rays compared to high-energy gamma rays. However, just as for protons, ionization damage from 10-keV X-rays is somewhat lower in thick field oxides. Thus, tests done with X-rays do not necessarily simulate the right amount of ionization damage in CMOS devices or in linear bipolar devices, which also contain thick oxides with relatively low electric fields. Differences up to a factor of two have been observed between ionization damage in X-rays and damage from high-energy gamma rays.

For work on the Interpoint converter, X-rays were only used to selectively irradiate specific internal devices within the converter. This is an effective way to determine how the overall converter response depends on degradation of various internal components.

C. Dose Rate Effects

Ionization damage depends on dose rate. For CMOS devices, damage usually anneals with time so that there is less damage under the low dose rate conditions that exist in space. However, the amount of annealing that occurs varies widely for different devices and processes. There is a standard method for dealing with this effect in MOS devices that uses annealing at high temperature *along with an overtest factor of 1.5* to *account for possible uncertainties and errors in the assumptions that are made about annealing*. That approach is based on technologies that are much newer than that of the TSD4426, and cannot be counted on to provide the correct result for that device.

Damage on linear devices can also depend on dose rate. In some cases damage anneals with time, but for other devices (with thick isolation oxides) the damage may actually be much higher at low dose rate.

For a complex device such as the Interpoint converter, it is particularly difficult to deal with dose rate effects. High temperature annealing may or may not successfully provide “end point” values that are equivalent to those in space. This is particularly complicated because bipolar and CMOS devices are both present within the converter. High temperature annealing cannot be counted on to provide a conservative estimate of damage under the low dose rate conditions in space without considerable diagnostic and modeling efforts.

The best way to deal with the dose rate issue is to do radiation tests at low dose rates which are closer to the actual conditions that are expected in space. Such tests are easily done, but require time periods of several months to complete. Recent data on converters at high and intermediate dose rates [up to167 and as low as 2 rad (Si)/m] has shown relatively small differences in failure level. This suggests that annealing may not provide a great deal of improvement in the failure levels that will occur in space. Testing at low dose rate is the only unambiguous way to evaluate this issue.

TESTS OF TSC4426 MOSFET DRIVER COMPONENTS

A. Standard Characterization Tests

Earlier test results from ICS were used by Interpoint when the TSC4426 was selected for use in the DC-DC converter. Those tests were done with a bias and post-radiation characterization voltage of 5 V, about 1/2 the voltage that is applied to those devices within the converter. The ICS tests showed very little degradation up to the highest radiation level, 90 krad(Si).

ICS performed a second series of tests on TCS4426 samples from the same lot used by Interpoint after the problem in the converters was identified. Again they observed no obvious degradation that could cause the converter to malfunction. The new tests were done with 10 V instead of 5 V.

B. Special Characterization Tests at JPL

JPL did a more detailed set of tests on the TCS4426, biasing devices during irradiation with waveforms and loading conditions that directly simulated device operation within the Interpoint converter. A 10-V power supply was applied during testing along with 10-V drive to one input. The input of Section A was driven with a 100-KHz square wave from a LM119 comparator with a 3.8k load resistance. The input of the other section was at ground. The output of Section A was loaded with 2000 pF, simulating the input capacitance of two power MOSFETs.

The devices were tested by irradiating them with the conditions specified above, removing the devices from the radiation source at specific intervals in order to do more thorough tests that were intended to verify their performance in the Interpoint power converter application.

The first tests that were done included special DC diagnostic tests as well as observations of the output pulse width, amplitude, rise time and fall time from the converter. Those initial tests showed that the TSC4426 exhibits a highly unusual failure mode under pulsed conditions that would not be apparent from standard DC tests. That response is shown in Figure 1 below. Prior to irradiation, the input and output are complementary regardless of pulse width (except for a small switching delay time), as expected for a basic inverter function. However, after sufficient internal damage has occurred the output pulse is prematurely cut off so that it *no longer follows the input pulse*. This appears to be the mechanism that causes the converter to fail. To reiterate, this is a highly unusual failure mode that would not normally be accounted for in standard evaluation tests. The reason for the failure is not understood. The manufacturer of the TCS4426 has been unwilling to provide a circuit diagram, limiting our ability to determine why this type of response occurs. However, it has been observed in all of the TSC4426 devices that we have tested to date, including samples from a newer lot of parts.

There are large increases in the power supply current after the TCS4426 fails in this mode, but those increases are only evident when the device is tested with a dynamic input signal. The current is large enough to cause extreme heating of the TSC4426 once it occurs, but again this is only evident when dynamic testing is done. Figures 2 shows how the current increases under static and dynamic conditions. Under static conditions there is an unusual increase in current at 3 krad(Si), but the current is much lower at higher radiation levels. The static tests done by ICS do not show any large increases in current, which is generally consistent with this result. The other two curves in Figure 2 show current increases for two different input pule width conditions,

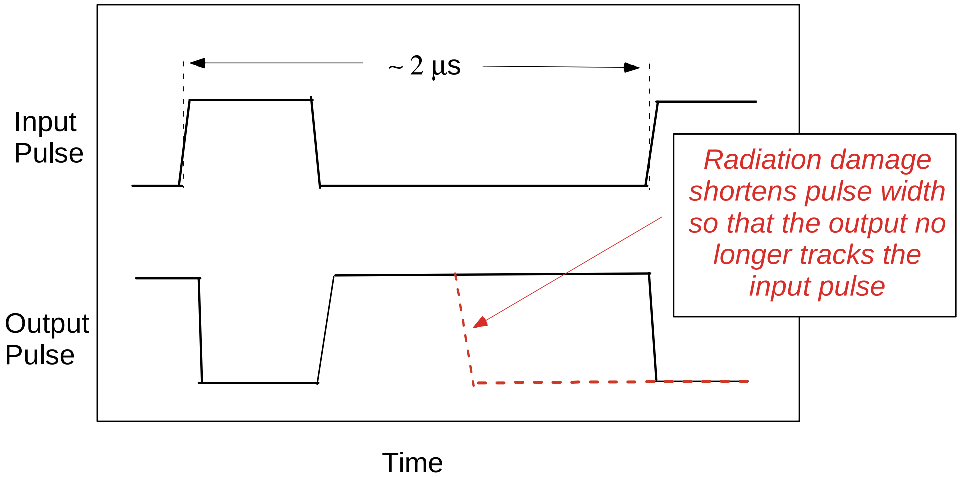

Figure 1. Dynamic failure mode exhibited by the TCS4426 after irradiation.

operating with a repetition rate of 500 kHz, the nominal operating frequency within the Interpoint converter. Note also that in these applications the TCS4426 gets extremely hot, to the point where it nearly burns the fingers of the operator when it is removed from the radiation test fixture for subsequent electrical tests.

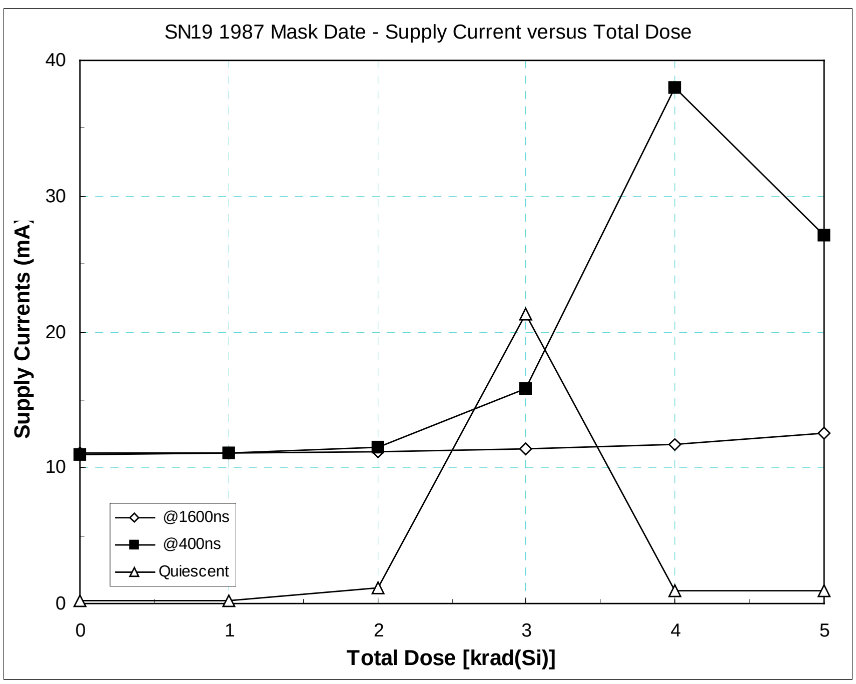

Figure 2. Increase in power supply current of a TSC4426 MOSFET driver vs. total dose.

C. Test Results with Cobalt-60 Gamma Rays

The results of tests of the TSC4426 at high dose rate with gamma rays are shown in Figure 3. The figure shows the output pulse width for various input signal widths, using a 500 kHz operating frequency, using successive irradiation steps of 1 krad(Si). After a total dose of 4-5 krad(Si), the converter can no longer provide the required output pulse length, and the maximum pulse length continues to decrease at successively higher total dose levels. Figure 3 shows typical results; tests of several devices have shown that this behavior occurs between approximately 3.8 and 5.4 krad(Si) for different test samples.

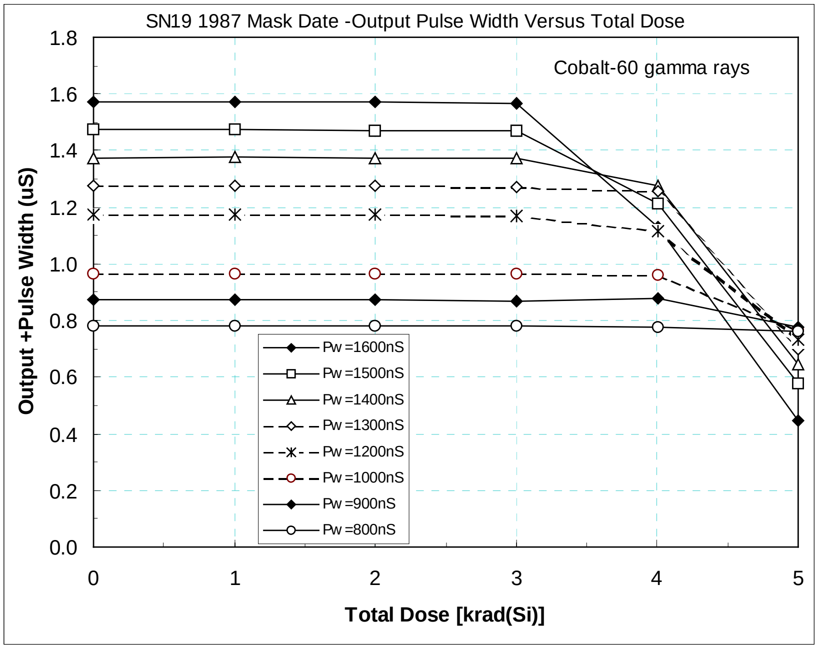

Figure 3. Output pulse width for various input pulse width conditions as a function of total dose (Cobalt-60 gamma rays).

A significant amount of annealing occurs after this type of damage is observed. The annealing is difficult to interpret because the chip gets extremely hot after it is damaged during dynamic tests. Unfortunately the test chips are mounted using an epoxy die attach method with much greater thermal resistance compared to devices that are mounted within the Interpoint power converter. Thus, it is quite likely that much less annealing will occur for devices within the converter compared to tests of individual components because the chip temperature will be much lower for devices that are mounted directly to the substrate of the converter. This important difference has to be taken into account when comparing test data on the TCS4426 components with test results for packaged converters.

D. Tests with Protons

Samples of the TSC4426 were also tested with 63-MeV protons. Those results are shown in Figure 4. They are qualitatively similar to those obtained during tests with gamma rays, but the failure level is about a factor of two higher compared to the gamma ray results. The proton test results may be affected by unavoidable differences in the length of time that devices were biased during the tests. Although the same dose rate -- 167 rad(Si)/m -- was used for both cobalt-60 and proton tests, it takes more time to turn on the proton test beam and to retrieve the samples after each test run was completed. Thus, the proton test samples are biased for a longer time period, which may affect the results, particularly after the current increases to approximately 30 mA when the device is approaching the total dose where failure occurs.

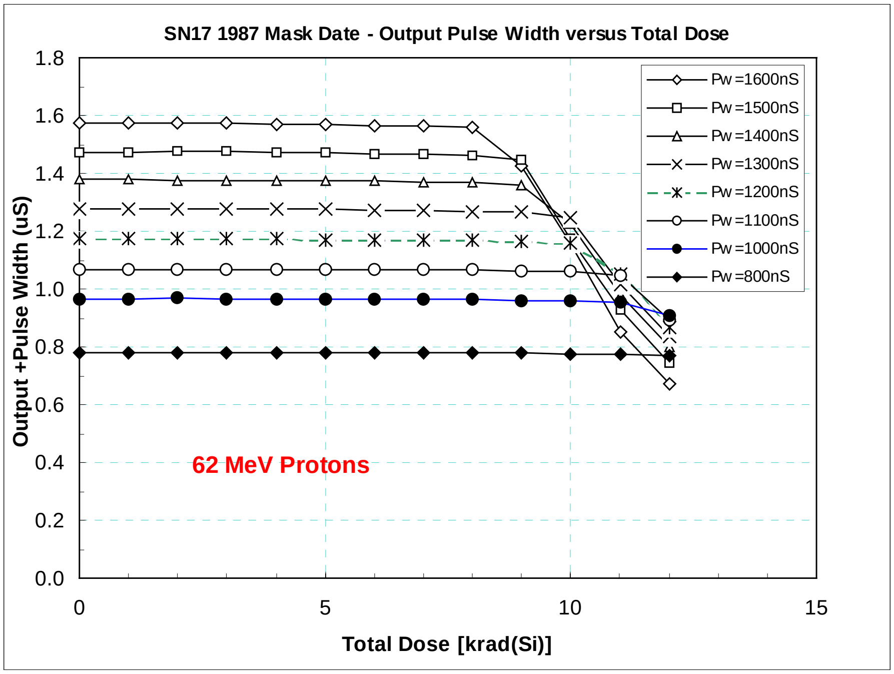

Figure 4. Output pulse width for various input pulse width conditions as a function of total dose (62-MeV protons)

Power Converter Tests

A. Critical Variables and Failure Definition

Power converter tests are less straightforward because the failure level is somewhat dependent on the conditions used for testing and electrical characterization. Converters that are tested without bias applied are damaged much less than converters that are tested with bias, as expected, and it appears that the specific load conditions that are applied during irradiation have little effect on converter degradation as long as bias voltages are applied, and the converter is operating.

However, the voltage and load conditions have large effect on how one defines failure for these devices. The converter can be used with input voltages from 16 to 40 volts, and the converter first indicates that it can no longer regulate when low input voltages are used in combination with high load conditions. Load conditions also have some effect, as shown in Table 2 for a converter that failed at 5 krad(Si).

Table 2. Example of the Dependence of Converter Failure Levels on Load Conditions

Load Condition	Start-Up Voltage	Drop-Out Voltage
50%	27.7	25.3
75%	28.5	25.9
100%	28.8	26.5

The interplay between loading conditions and the voltage required for failure is potentially confusing, and makes it difficult to compare results from different tests. Some tests have used 28 volts for the worst-case input voltage with light loading, while others have used higher input voltage conditions to define failure. However, our evaluation of the load dependence has shown that the failure level depends only on the total load, not the way that it is distributed between the two outputs on dual versions of the converter. As discussed earlier, heating of the converter may also play a role in the failure level. The LMA results for one converter that was irradiated without a heat sink are significantly higher than the results for three other converters that were irradiated with a heat sink (see Table 1).

The failure definition also depends on the amount of voltage change that is allowed. Some tests have used ±5% of the nominal 5-V output voltage, while others have used more relaxed criteria.

Finally, the dose rate and type of radiation (proton or gamma ray) may also affect results.

B. Tests with Gamma Rays

The JPL gamma ray tests were done using a fixed load condition (87% of maximum; 1.4 A load on the positive output and 0.7 A on the negative output) with an input voltage of 28 V. The output voltage and current were continuously monitored during irradiation as well as the baseplate temperature of the module. Special heat sinks were attached to the modules to reduce heating. Typical operating temperatures were 32-39 °C; without the special heat sinks the temperature would increase above 60 °C.

At intervals of 1-krad(Si) the radiation source was lowered and a more complete characterization of converter performance was done, using programmable electronic loads and power supplies. For the dual version of the converter, those tests involved the following:

1. <u>Load Performance with Fixed Input Voltage Conditions</u>. This test consisted of holding the input voltage at each of three voltages (16, 28 and 40 V) and then varying the positive load from 10 to 100% in combination with varying the negative load from 0 to 90%. This allowed the load conditions to be measured that cause the converter to go out of regulation.

2. <u>Input Voltage Performance with Fixed Output Load Conditions</u>. This test consisted of holding the load conditions at each of three currents (50%, 75% and 100%, with a "2/3" "1/3" split between the positive and negative outputs, and then ramping the input voltage from 16 to 40 V to determine the input voltage conditions required for regulation. The input voltage was also ramped down to determine how the converter performed after regulation when the input voltage was reduced.

Similar tests were done for single versions of the converter, but of course there is only a single load with simplified the matrix of test conditions that were used to evaluate performance after each 1-krad(Si) increment of total dose.

Numerous tests were done of different converters, but many of the tests involved changing various conditions -- biasing, annealing steps, etc. -- and the results for those tests are described in Subsection E.

The results for the one converter that was tested using cobalt-60 gamma rays with the same conditions used by ESA and LMA in their tests is summarized in Table 3 below. The failure level was slightly lower than the mean failure level that was observed by LMA for the converters that they tested (see Table 1). Note however that they used a lower dose rate -- 2 rad(Si)/m -- for their tests.

Table 3. Cobalt-60 Test Results for Several Converters

Part Type	Serial Number	Bias Voltage	Fail Voltage	Dose Rate [rad(Si)/m]	Load Condition	Failure Dose [krad(Si)]
SMHF2805S/KR	188 DC9926	28	28	167	87%	3.9

C. Tests with Protons

The JPL converter tests with protons irradiated the entire converter, using 63-MeV protons at the University of California, Davis. Those test results are shown in Table 4 for two converters. Note that the failure levels of those devices is about 45% higher than the failure level of the single converter that was tested by JPL with gamma rays under similar test conditions, but only about 20% higher than the mean level of the converter tests done by LMA under similar conditons. That result is somewhat inconsistent with the results for the TSC4426, which were done during the same test period. It suggests that failure in the converter is not solely the result of degradation of the TSC4426, but also depends on degradation of other internal components within the converter.

Table 4. Converter Test Results with 63-MeV Protons

Part Type	Serial Number	Bias Voltage	Test/Fail Voltage	Dose Rate [rad(Si)/m]	Load Conditions	Failure Dose [krad(Si)]
SMHF2805D	1 DC9906	28	28	167	87%	5.64
SMHF2805D	14 DC9840	28	28	167	87%	5.65

The failure level increased somewhat when the input voltage was increased. For example, failures for Vin = 30 V at were observed at 5.89 and 5.93 krad(Si). Failures for Vin = 40 V occurred at 6.52 and 6.53 krad(Si). Thus, relaxing the input requirements shifts the failure level upward by as much as 20%.

D. Selective Tests with X-Rays

Some diagnostic tests were done using 10-keV X-rays. The X-ray source can be collimated, providing a way to selectively irradiate individual devices within the converter. Initial tests were done to irradiate only the TSC4426 device within one converter. Those tests showed converter failure at about 12 krad(Si), which is about the same level at which TSC4426 devices failed when they were irradiated with protons, but there is some uncertainty in this result because the collimator slipped during the irradiation.

Additional tests were done selectively irradiating other active elements within the converter after the converter no longer worked with minimum input voltage conditions due to radiation damage of the TSC4426. Two transistors, used as part of an internal power supply, also affected the converter. Irradiating the npn transistor to 40 krad(Si) increased the minimum input voltage from 18.5 to 22.5 V (with a fixed load condition). Subsequent selective irradiation of the pnp transistor to 10 krad(Si) increased the minimum input voltage by an additional two volts. These results suggest that other active devices within the converter also contribute to failure, particularly the discrete pnp transistor in the internal power supply that provides the voltage to the TSC4426.

This may be one reason why the differences between proton and gamma ray tests of the converters is smaller than the difference in proton and gamma ray tests of the TSC4426 component tests.

E. Test with Gamma Rays Using Special Conditions or Devices

Most of the converter tests done by JPL used special conditions that differed so much from the other converter tests that they have to be considered separately. With one exception, those tests were done at a dose rate of 167 rad(Si)/m. The results of these tests are shown in Table 5. They represent four different special conditions that are described in the subsections below.

1. <u>Irradiation followed by Annealing</u>

Two converters were subjected to a special test sequence that consisted of irradiation in 2 krad(Si) steps, waiting for 48 hours before the irradiation was continued. The purpose of those tests was to determine how the failure level would be changed by allowing the part to anneal at room temperature before the irradiation was resumed. Both converters failed during the third step [on the way to a cumulative level of 6 krad(Si)], at levels of 5.2 and 5 krad(Si). The mean failure level with that particular sequence was about 20% higher than that of the converter that was tested without allowing extended time periods between successive irradiation steps. The result suggests that although some annealing occurs, it is significantly less than one would expect from studies on similar device technologies in the mid-1980 time period. However, those older devices failed because of changes in the threshold of gate oxides.

2. <u>Initial Unbiased Irradiation followed by Biased Irradiation</u>

One part was subjected to an initial irradiation of 6 krad(Si) with no bias applied. It was electrically tested afterwards, and then irradiated under bias. The incremental total dose required to make that part fail was 3.2 krad(Si). This shows that parts that are irradiated in an unused (or "spare" mode) will be somewhat less affected by irradiation, but that the damage that occurs when they are unbiased will cause them to fail with smaller incremental total dose compared to devices that are irradiated under bias. However, the data under this rather arbitrarily selected set of conditions is not sufficient to determine how various sequences of unbiased and biased irradiations would actually affect converter operation.

3. <u>Part with TCS4426 Devices from Newer Date Code</u>

One converter was tested that used a TCS4426 MOSFET driver from a newer date code. That device failed at 4.6 krad(Si), which is within the range of failures that were observed for converters with the older date code of TSC4426 devices. Thus, it appears that the newer date code does not affect the hardness level of the converter.

4. <u>Reworked Part with TCS4429 MOSFET Driver</u>

One converter was provided that substituted a different MOSFET driver chip, the TCS4429. That part worked satisfactorily up to 70 krad(Si), the highest level in the test. This suggests that substituting the alternative driver chip will solve the problem of the unusually low failure levels of the Interpoint power converter. However, more work is needed to verify that the TSC4429 will not be affected by the same type of failure mode.

Table 5. Test Results for Converters Using Non-Standard Test Conditions or Internal Parts

Part Type	Serial Number	Special Conditions	Bias Voltage	Fail Voltage	Load Condition	Dose Rate [rad(Si)/m]	Failure Dose [krad(Si)]
SMHF2805 DF/MR	9 DC9928	2 krad steps followed by annealing	28	28	87%	167	5.2
SMHF2805 DF/KR	23 DC9849	2 krad steps followed by annealing	28	28	87%	167	5.0
SMHF2805 DF/KR	33 DC9849	6 krad unbiased initial irradiation followed by biased irradiation	28	28	87%	167	6 (unbiased) + 3.2 biased
SMHF2805 DF/KR	11 DC9940 reworked	Newer lot of TCS4426	28	28	87%	167	4.6
SMHF2805 DF/KR	32 DC9849* reworked	**TCS4429** substituted for TCS4426	28	N/A (part did not fail)	87%	2520	not failed at 70

* not actually marked

SUMMARY AND CONCLUSIONS

Several different radiation tests have been done on the SMHF-series of Interpoint power converters. For converters that were tested with Cobalt-60 gamma rays using normal heat sinking (a very important detail), failures occurred at total dose levels between 3.9 and 6.5 krad(Si) for several different devices that were tested by three groups: ESA, LMA and JPL. The mean failure level under these conditions was 4.9 krad(Si). There is some indication that tests at lower dose rates -- 2 rad(Si)/m compared to 167 rad(Si)/m -- raises the failure level by about 20%. That is a very small difference considering the amount of time required to irradiate the devices under these conditions. It raises the distinct possibility that these devices may not anneal very much during actual conditions in space.

Proton tests of the entire converter with 63 MeV protons show a mean difference of about 30% between the mean failure level of converters that were tested with gamma rays. That difference is consistent with the expected differences in charge recombination for thick oxides, such as the field oxide of CMOS devices. However, the median energy of the proton spectrum for Jason is actually higher, about 120 MeV. Thus, there may be less difference between proton damage in the actual environment than observed in the laboratory tests. It is also likely that degradation of other components within the converter may contribute to the failure mechanism. The diagnostic tests with the 10-keV X-rays show that degradation of discrete transistors also affect converter operation.

The mean failure level of these converters is more than a factor of two below the required total dose level for five years of operation. Unless additional shielding can used to reduce the radiation level to about 5 krad(Si), this presents a very high level of risk for the converter in this application.

It is possible that sufficient annealing will occur in the low dose rates that will actually occur to raise the failure level above the required radiation level. However, the very small differences between failure levels of converters that were irradiated for more than three days (at 2 rad/m) compared to converters that were irradiated for less than two hours (167 rad/m) is not encouraging, and suggests that relatively little annealing may actually occur for these devices. This is further borne out by the very small differences in failure level for a converter that was irradiated in steps, with 48 hour annealing periods between successive irradiations, compared to converters that were irradiated without allowing incremental time for annealing. The only way to resolve this is to do irradiations at low dose rate, which will require several months to complete.

Finally, the tests of the TSC4426 devices have shown that failure in the converters is the result of a very unusual failure mode that cannot be easily explained. It is not at all clear why the inverter (which should be independent of pulse width) suddenly is no longer able to provide pulse widths beyond certain limits after degradation. The failure may be due to either gate threshold shift or field oxide leakage, and is strongly affected by temperature. The underlying reasons for this response need to be understood before using any circuit that relies on that device at radiation levels above the point where it fails from radiation.

Appendix

to

Radiation Test Results for Interpoint Power Converters

Gary M. Swift

August 29, 2001

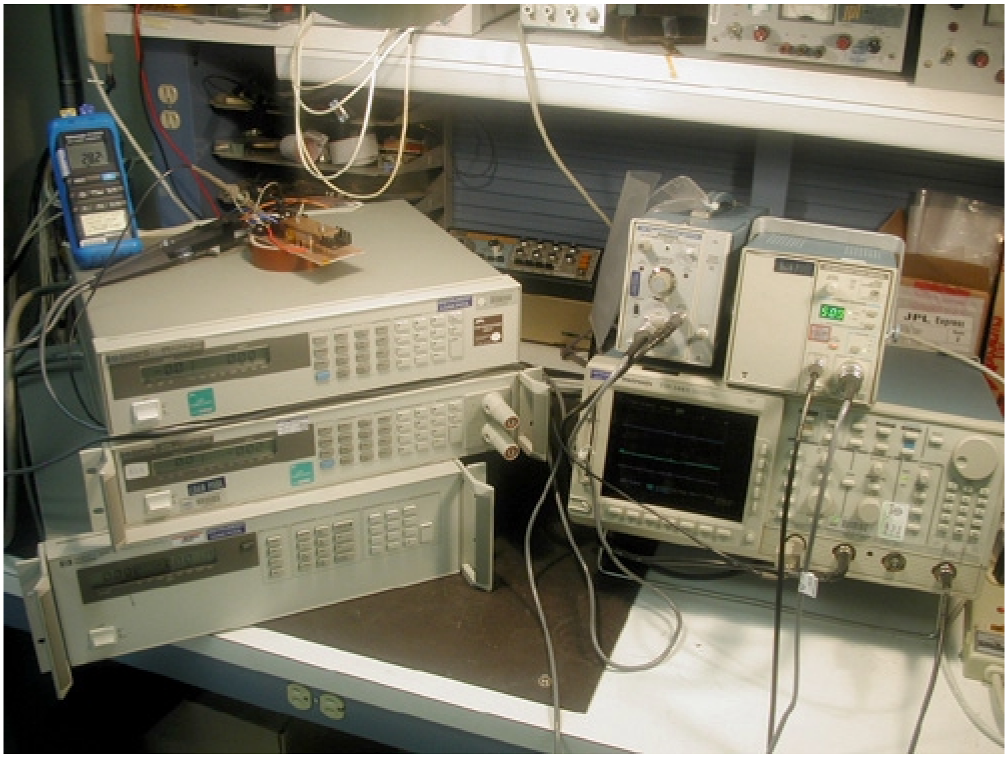

Photo 1: Measuring test setup consists of two programmable electronic loads and a power supply (shown stacked on the left side.) The oscilloscope was used to monitor current in and out of the converter to check for proper operation (no oscillations).

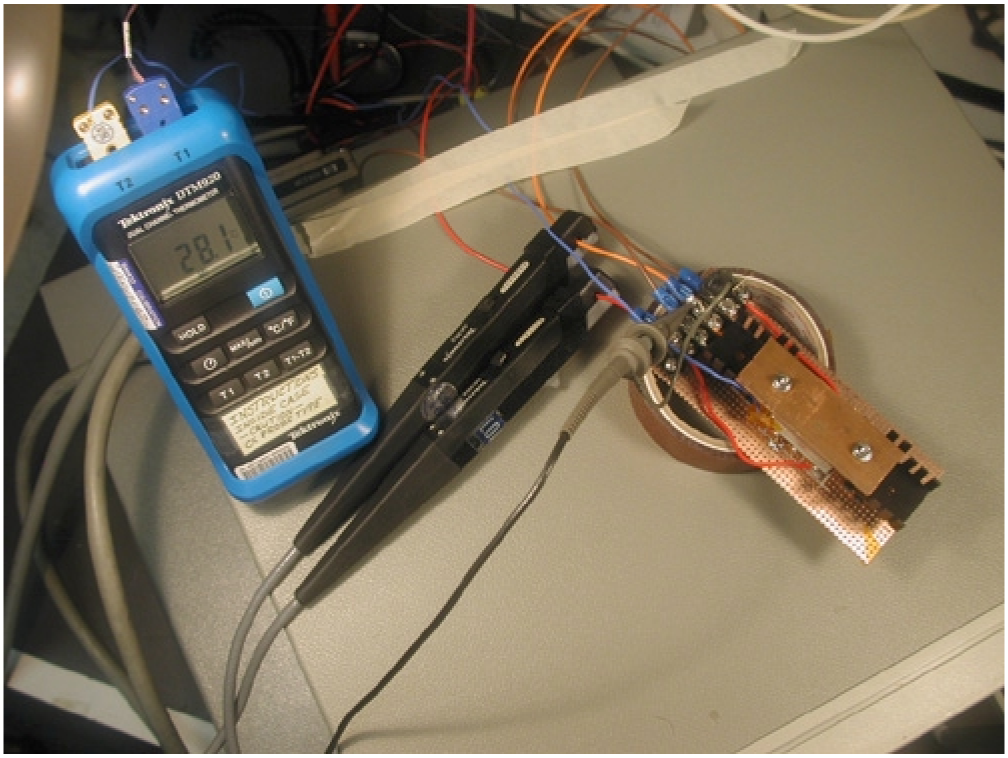

Photo 2: A close-up of the converter in the heat sink on the test board. The blue meter is monitoring converter base plate temperature. The current probes monitoring the input and output wires are shown in the center of the photo.

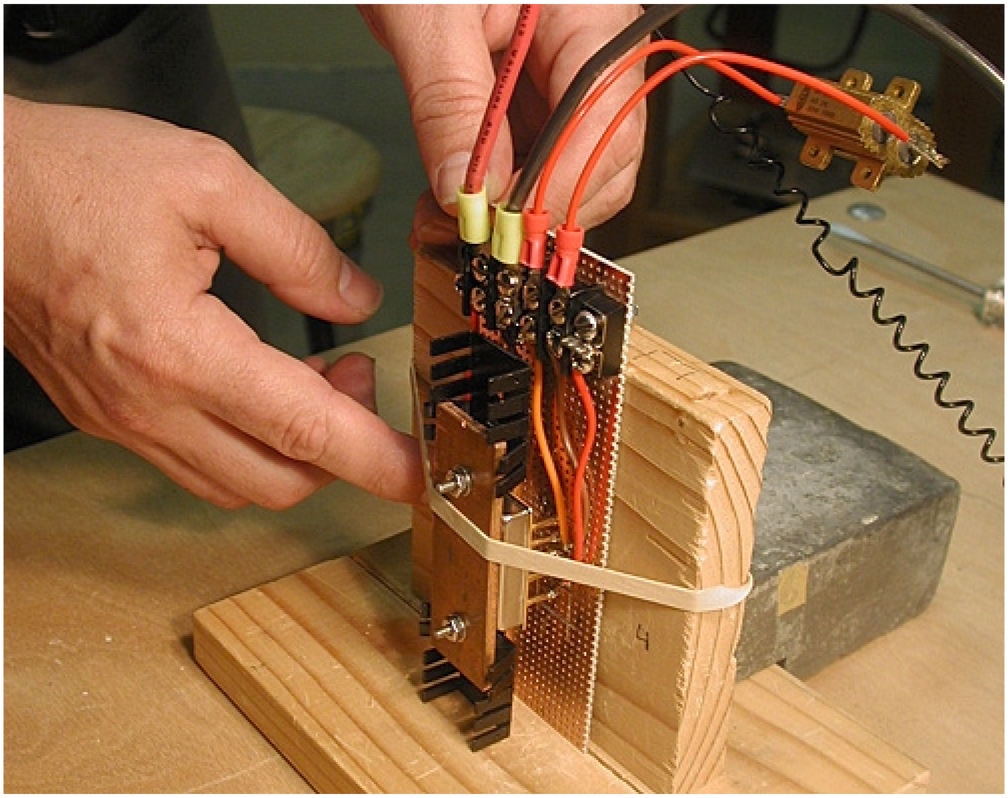

Photo 3: Close-up view of converter being placed in position for radiation. Note the fixed load resistor dangling behind the test board was replaced in later tests with electronic loads for continuous monitoring of the output.

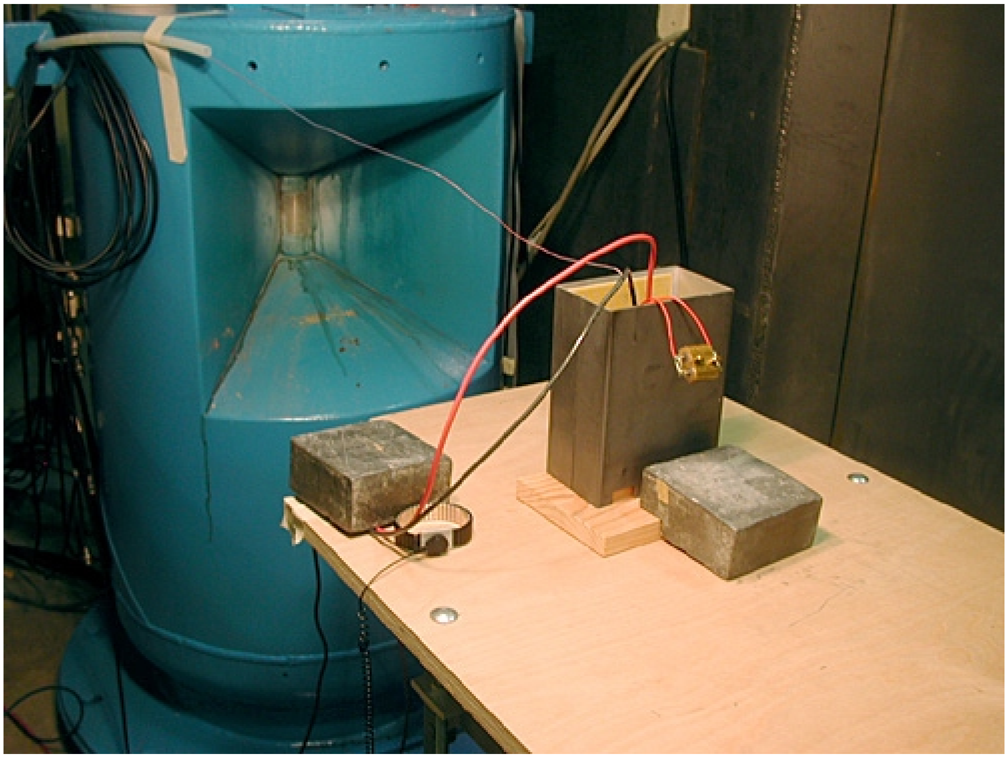

Photo 4: Single output converter (s/n 188) set in front of the Cobalt-60 irradiator inside lead-aluminum equilibrium box for dose rate of 10 krad(Si)/hr. Input voltage and current is continuously recorded using a computer GPIB connected to a programmable power supply (HP 6622, not shown).

Photo 5: Delidded converter being prepared for x-ray irradiation of individual components within the converter.

Photo 6: Closing the cover on the x-ray irradiator. In foreground, test setup including laptop PC for recording test measurements, power supply, and electronic load.

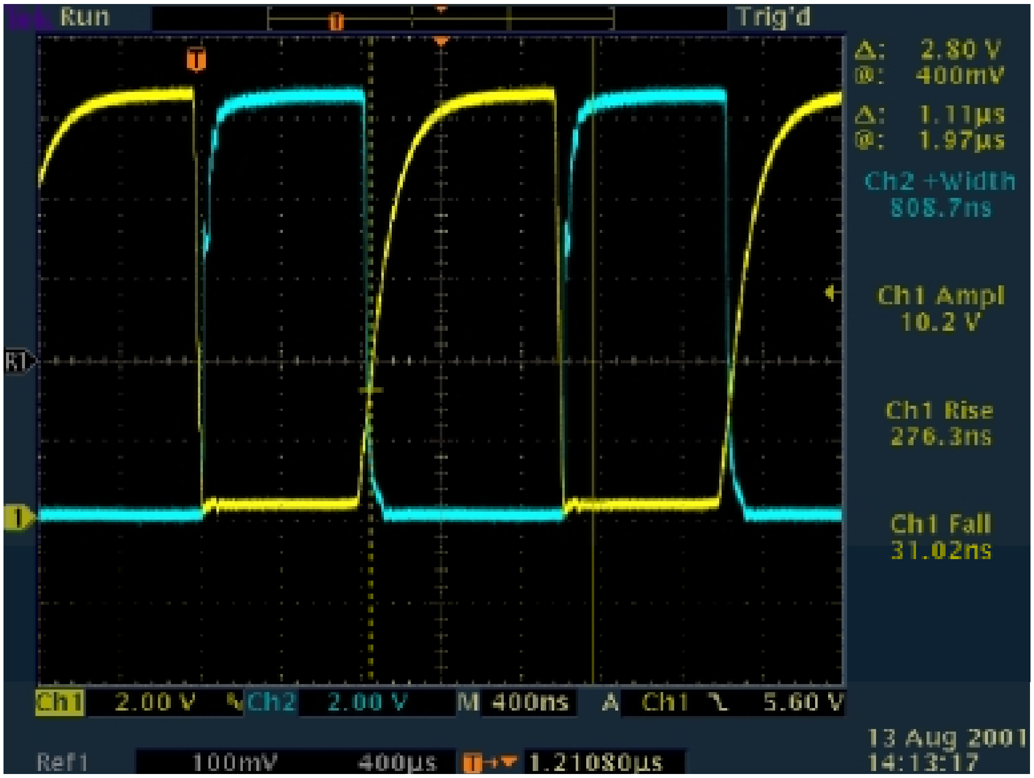

Photo 7: Waveform captures of input (yellow) and output (blue) of TSC-4426 inside working converter. Note the pulse width output for the given Vin and load is 809 ns.

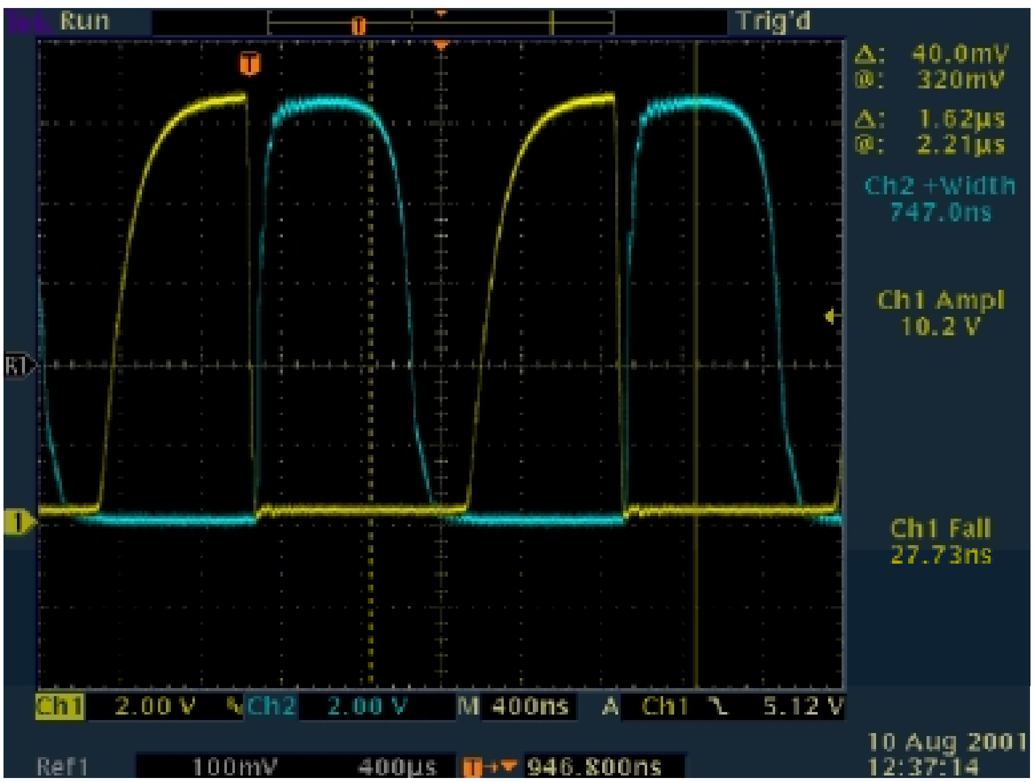

Photo 8: Waveform captures of input (yellow) and output (blue) of TSC-4426 inside converter irradiated to just beyond the failure point. Note the pulse width is truncated to 747 ns, and as a result, the output is no longer regulating to 5.0 volts.